Generation of 28-fs pulses from a mode-locked ytterbium fiber oscillator

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Abstract: An ultrashort-pulse, mode-locked ytterbium-doped fiber laser has been developed. The group-delay dispersion was compensated with a grating pair inside the cavity. A broad spectrum from 1000-nm to 1120-nm was obtained without intracavity compensation of third-order dispersion. A 0.7-nJ pulse as short as 28.3 fs was obtained with a repetition rate of 80 MHz. To our knowledge, this is the shortest pulse reported from an Yb fiber laser oscillator.

OCIS codes: (140.3510) Laser, fiber; (320.7090) Ultrafast lasers

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References and links

1. B. Ortac, O. Schmidt, T. Schreiber, J. Limpert, A. Tunnermann, and Ammar Hideur, "High-energy femtosecond Yb-doped dispersion compensation free fiber laser," Opt. Express **15**, 10725-10732 (2007).
2. F. O. Ilday, J. Buckley, L. Kuznetsova, and F. W. Wise, "Generation of 36-femtosecond pulses from a ytterbium fiber laser," Opt. Express **11**, 3550-3554 (2003).
3. M. E. Fermann, M. J. Andrejco, Y. Silberberg, and A. M. Weiner, "Generation of pulses shorter than 200 fs from a passively mode-locked Er fiber laser," Opt. Lett. **18**, 48-50 (1993).
4. M. L. Dennis and I.N. Duling III, "Third-order dispersion in femtosecond fiber lasers," Opt. Lett. **19**, 1750-1752 (1994).
5. J. R. Buckley, S. W. Clark, and F. W. Wise, "Generation of ten-cycle pulses from an ytterbium fiber laser with cubic phase compensation," Opt. Lett. **31**, 1340-1342 (2006).
6. I. Hartl, T. R. Schibli, A. Marcinkevicius, D. C. Yost, D. D. Hudson, M. E. Fermann, and J. Ye, "Cavity-enhanced similariton Yb-fiber laser frequency comb: 3×10^{14} W/cm^2 peak intensity at 136 MHz," Opt. Lett. **32**, 2870-2872 (2007).
7. H.Lim, F. O. Ilday, and F. W. Wise, "Generation of 2-nJ pulses from a femtosecond ytterbium fiber laser," Opt. Lett. **28**, 660-662 (2003).
8. J. W. Nicholson, J. Jasapara, W. Rudolph, F. G. Omenetto and A. J. Taylor, "Full-field characterization of femtosecond pulses by spectrum and cross-correlation measurements," Opt. Lett. **24**, 1774-1776 (1999).
9. A. Galvanauskas, "Ultrashort Pulse Fiber Amplifiers" in *Ultrafast Lasers, Technology and Applications*, M. E. Fermann, et al. ed. (Marcel Dekker, New York, NY 2003).
10. L. Shah, Z. Liu, I. Hart, G. Imeshev, G. Cho, and M. Fermann, "High energy femtosecond Yb cubicon fiber amplifier," Opt. Express **13**, 4717-4722 (2005).
11. S. Zhou, L. Kuznetsova, A. Chong, and F. W. Wise, "Compensation of nonlinear phase shifts with third-order dispersion in short-pulse fiber amplifiers," Opt. Express **13**, 4869-4877 (2005).
12. D. N. Papadopoulos, Y. Zaouter, M. Hanna, F. Druon, E. Mottay, E. Cormier, and P. Georges, "Generation of 63 fs 4.1 MW peak power pulses from a parabolic fiber amplifier operated beyond the gain bandwidth limit," Opt. Lett. **32**, 2520-2522 (2007).
13. A. Chong, L. Kuznetsova, and F. W. Wise, "Theoretical optimization of nonlinear chirped-pulse fiber amplifiers," J. Opt. Soc. Am. B **24**, 1815-1823 (2007).
14. L. Kuznetsova and F. W. Wise, "Scaling of femtosecond Yb-doped fiber amplifiers to tens of microjoule pulse energy via nonlinear chirped pulse amplification," Opt. Lett. **32**, 2671-2673 (2007).

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1. Introduction

Fiber lasers have attracted attention as practical alternatives to solid-state lasers, offering compact size, great stability, and convenience for alignment. Recently, ytterbium (Yb) has

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proven to be a competitive ion delivering short pulses and high energy at 1 μm. The pulse energy of a mode-locked Yb-doped fiber oscillator can be up to 265 nJ [1], and the pulse duration can be down to several 10 fs, which makes it more attractive for ultrashort pulse operation than other fibers. In particular, an Yb fiber amplifier can provide a high repetition rate of several tens of megahertz with high-peak power pulses, which cannot be matched by solid-state lasers.

In the past few years, several researchers have reported sub 40-fs pulses from Yb fiber lasers. It is well known that a broadband spectrum is obtained by optimizing the group-delay dispersion (GDD) of the cavity. An internal grating pair is a good choice to compensate fiber dispersion with a megahertz repetition rate. Ilday et al. demonstrated a 36-fs Yb fiber laser by optimizing group-delay dispersion (GDD) inside the cavity [2]. That was the shortest pulses produced from Yb fiber laser without high-order dispersion compensation. The effects of third-order dispersion (TOD), which limits the pulse duration was subsequently studied [3,4]. Buckley et al. reported a 33-fs Yb fiber laser using a prism-grating sequence to reduce GDD and TOD inside the cavity [5].

Recently, a record peak intensity of 3×10^{14} W/cm^2 at the focus of an external enhancement cavity was demonstrated, which is very useful for investigating highly nonlinear phenomena [6]. Shorter pulse duration with a 100-MHz repetition rate Yb-fiber oscillator is attractive for the enhancement-cavity applications.

In this work, we demonstrate an Yb fiber oscillator with a repetition rate of 80 MHz. The cavity dispersion was compensated by a grating pair inside the cavity. Although only the cavity GDD was compensated in the cavity, a pulse width of 28.3 fs was obtained by an external prism pair compressor. We believe this to be the shortest pulses obtained from an Yb fiber laser. The effect of TOD on the cavity will be discussed.

2. Experimental Setup and results

A unidirectional ring cavity is employed in this experiment (Fig. 1). Highly doped Yb fiber (effective area 30 μm^2, 1.3×10^4 ppm doping) with a length of 30 cm was pumped by a fiber-coupled pump diode delivering 300 mW at 976 nm. The pump light was coupled into the ring cavity via a wavelength-division multiplexer (WDM). The polarization state of the mode-locked pulses was adjusted with three wave plates before the output coupler. Although one of the quarter waveplates is typically placed at the fiber input, the order and the place of these waveplates do not affect the polarization state at the fiber input. An isolator forced unidirectional ring operation. The fiber laser generated positively chirped pulses, which were compensated with a 600-groove/mm grating pair in the cavity. A grating pair provides negative GDD, which compensates the positive GDD of fiber in the cavity. The total fiber length is 170 cm, and the repetition rate is 80 MHz.

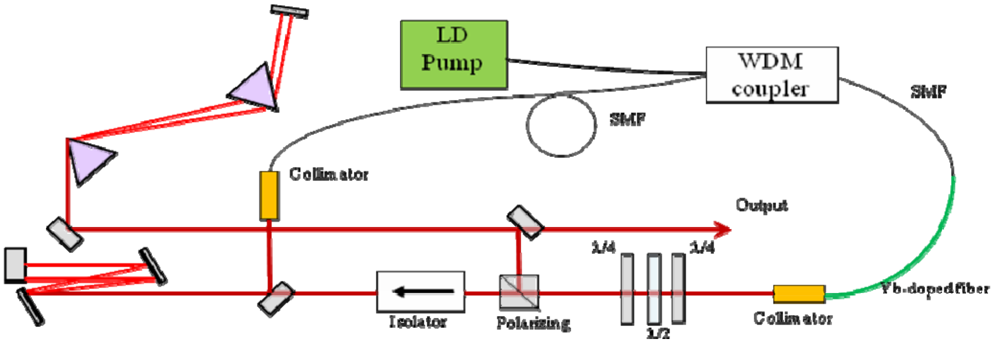

Fig. 1. Schematic diagram of the Yb fiber oscillator system SMF: single mode fiber (effective area 30μm^2)

The collimators were adjusted carefully to reduce the limitation of the achievable pulse spectrum. It is well known that the reducing the cavity dispersion can shorten the pulse duration [7]. Thus, the distance of the gratings inside the cavity was adjusted to vary the GDD of the cavity to optimize the spectral bandwidth. The spectra of the pulses are presented in Fig. 2. The peak of the spectrum at 976 nm is related to the unabsorbed pump light. The dashed curve represents the broadest spectra at 30 mm grating separation, covering the range from 980 nm to 1120 nm, which almost covers the total emission spectrum of the Yb fiber. It could be possible to generate transform-limited pulses as short as 25 fs by using this spectrum. However, the shortest pulse did not correspond to the broadest spectrum. It would be because of some uncompensatable phase at a grating distance of 30 mm. The calculated net cavity GDD is roughly $-3\pm1\times10^3$ fs^2, and the calculated GDD of the total fiber is about $3.9\pm0.1\times10^4$ fs^2 at 1050 nm in this condition. The solid curve plots the spectrum at a grating distance of 28 mm with a net cavity GDD of nearly zero, where the shortest pulse was obtained.

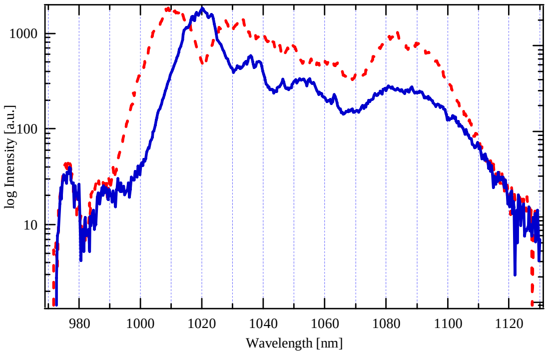

Fig. 2. Spectrum of the pulses with grating distances of 28 mm (solid curve) and 30 mm (dashed curve)

A prism pair was employed to dechirp the residual dispersion of the output pulse externally to the cavity. Since dispersion of the output pulse cannot be induced and is difficult to simulate, several prisms (e.g., SF6, SF14 and SF57) with different TOD-to-GDD ratios were investigated in a search for the best compensation with the shortest pulse width. The SF14 prism pair was chosen because it can provide the best TOD-to-GDD ratio to reduce the residual dispersion in this experiment. We varied the GDD and TOD by adjusting the distances between the prisms and the insertion of the two prisms. The shortest pulses were obtained at a distance between the prisms of 845 mm with two insertions of 8 mm and 10 mm. The calculated GDD (TOD) of the SF14 prism pair is -1320 fs^2 (-18500 fs^3) with a TOD-to-GDD ratio of 14 fs at the center wavelength of 1050 nm.

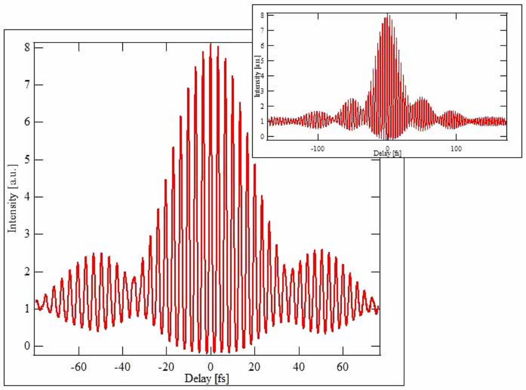

Fig. 3. Measured interferometric autocorrelation Inset; long-range autocorrelation

The temporal profile of the output pulse was obtained by an interferometric autocorrelation technique. Fig. 3 depicts the measured autocorrelation trace. The pulse shape and phase were reconstructed by the phase and intensity from cross correlation and spectrum only (PICASO) [8] algorithm. As a result (Fig. 4), the FWHM duration of the pulse is 28.3 fs, which is near the Fourier transform pulse width of 27.6 fs. Small structures in the wings would be caused by uncompensated TOD.

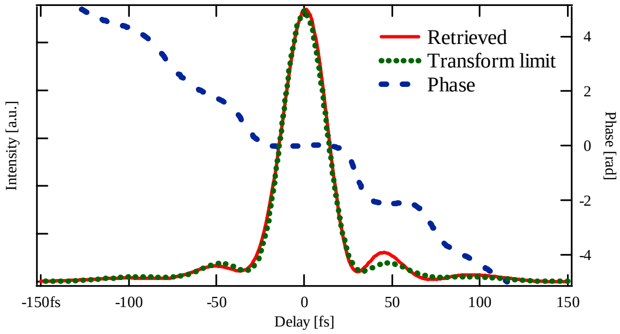

Fig. 4. Pulse shape retrieved by PICASO. Solid curve: retrieved pulse shape. Dashed curve: retrieved phase. Dotted curve: transform limit pulse

The average output power was 56 mW at 80 MHz. Since the unabsorbed pump power was negligibly small, the calculated pulse energy is 0.7 nJ with good pulse quality. When the pump power is above 200 mW, the mode-locking is initiated immediately by shaking the grating or tapping the mirror holder. The fluctuations in pulse energy are 0.1%, and mode-locked operation was stable for days.

3. Discussion of the dispersion

The net GDD and TOD in our cavity are estimated to be $0 \pm 1 \times 10^3$ fs^2 and $1.55 \pm 0.02 \times 10^5$ fs^3, respectively. One cannot obtain 30-fs pulses if the uncompensated TOD is such a huge value. Thus, there should be some nonlinear phase shift in the cavity for the residual chirp compensation.

The possibility of TOD compensation with self-phase modulation (SPM) was predicted by Galvanauskas [9] and theoretically demonstrated with pulse propagation dynamics by the nonlinear Schrödinger equation [10]. Some groups reported that the nonlinear phase shift originating from the SPM effect compensates for the TOD mismatch between the stretcher and compressor in fiber CPA [10-14]. The SPM induces the phase shift of the chirped pulses, which acts to narrow the temporal pulse duration. By our consideration, the cubic phase caused by the residual TOD in our cavity could be compensated by this nonlinear phase shift.

If the SPM effect is too strong on the other hand, the dispersion of the pulse could not be compensated completely. Although the nonlinear phase shift in the cavity cannot be estimated exactly, the GDD value without the consideration of the nonlinear effect can be reconstructed in each position of the cavity. The residual GDD and TOD values are estimated by PICASO. The GDD values can be counted backward to the cavity. As a result, the shortest pulse appears near the exit point of the Yb-doped fiber. The SPM effect occurs in this short section because there is no SMF after the Yb-doped fiber in our cavity. Thus, SPM occurs moderately, and the nonlinear phase shift could work well for the chirp compensation.

4. Conclusion

In conclusion, we have developed a mode-locked Yb fiber oscillator that produced nearly transform-limited 28.3-fs pulses at a center wavelength of 1050 nm with 0.7 nJ at 80-MHz repetition rate. To our knowledge, this is the shortest pulse obtained from an Yb fiber laser. The intracavity dispersion was compensated simply with a grating pair. The amplification of

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the presented ultrashort-pulse oscillator with high repetition rate and good quality is expected to be employed in numerous applications.

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